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Influence of Cotton Height on Injury from Flumioxazin and Glyphosate Applied POST-Directed

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In 2004 and 2005, glyphosate + diuron and flumioxazin + MSMA were applied POST-directed to cotton at 20, 30, 40, and 50 cm in height. Herbicides were directed to either the lower 2 cm of the cotton stem or to the lower 50% of the cotton stem to determine the impact of application timing and placement on cotton response. Glyphosate + diuron resulted ≤ 22% injury when applied high on the stem and ≤ 8% injury when applied low on the stem. Regardless of application placement or timing, no yield reductions were observed as a result of glyphosate + diuron application. Conversely, flumioxazin + MSMA applications resulted in 93 and 64% injury when applied high POST-directed (HPD) to 20- and 30-cm cotton, respectively. Low POST-directed (LPD) applications caused 33 and 23% injury to 20- and 30-cm cotton, respectively. In both years, HPD applications of flumioxazin + MSMA on 20-cm cotton resulted in excessive yield loss (94 to 87%), whereas yield loss was only noted in 30-cm cotton in 2004. No yield loss was observed in 40- or 50-cm cotton. Additionally, LPD applications of flumioxazin + MSMA, though causing significant visual injury, did not result in a yield reduction at any application timing. Although cotton became more tolerant to flumioxazin + MSMA as the season progressed, the research suggests that applications of flumioxazin should be made with precision or delayed until cotton reaches 40 cm in height.

Nomenclature: Diuron; flumioxazin; glyphosate; MSMA; Cotton, *Gossypium hirsutum* L. 'DPL 555', GOSHI.
Key words: Crop injury, herbicide application.

Few herbicides have been registered for broadcast applications to cotton foliage. This has led many cotton producers to apply herbicides in an over-the-top fashion early in the season, then avoid foliage with POST-directed (PD) applications later in the season. This is particularly true for glyphosate-resistant[1] cotton, which can only receive over-the-top applications of glyphosate before the formation of the fifth leaf (Anonymous 2006a). Therefore, even some transgenic cotton still requires PD herbicide applications for season-long weed control.

Historically, many cotton producers relied on cyanazine for lay-by weed control because of the wide-spectrum of weeds controlled, soil residual activity, and lack of carryover concerns (Vencill 2002). However, cyanazine is no longer registered for this use. As a replacement for cyanazine, many producers have switched to glyphosate alone or glyphosate combinations at lay-by. Although glyphosate is effective on many weed species, it often fails to control morningglory (*Ipomoea* spp.), nutsedge (*Cyperus* spp.), and larger weeds that escaped previous herbicide applications (Fischer and Harvey 2002; Lanie et al. 1994; Wilson and Worsham 1988). Even greater concern has recently arisen with the confirmation of glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronq.] (Main et al. 2004) and Palmer amaranth (*Amaranthus palmeri* S. Wats.) (Culpepper et al. 2006). Additionally, glyphosate has no soil activity (Noruma and Hilton 1977; Sprankle et al. 1975) and is only capable of controlling weeds that have emerged at the time of application. Considering the fact that glyphosate has no residual activity and may not control certain weeds, cotton producers in the southeastern United States may include other herbicides (such as diuron) to improve weed control over glyphosate alone. Although new cotton technologies, such as enhanced glyphosate-resistant[1] and glufosinate-resistant[2] allow over-the-top applications throughout the season, the use of multiple herbicides with differing mechanisms-of-action is still necessary for resistance management. Considering the need for additional mechanisms of action, soil residual activity, efficacy, and relatively low cost, glyphosate + diuron combinations are likely to become more common to overcome the deficiencies of using one herbicide alone.

Flumioxazin is an *N*-phenylphthalimide herbicide that has been registered for PRE use in peanut (*Arachis hypogaea* L.) and soybean [*Glycine max* (L.) Merr], and PD in cotton. Flumioxazin is a useful lay-by herbicide because it has been shown to provide excellent control of pigweeds (*Amaranthus* spp.), sicklepod [*Senna obtusifolia* (L.) H. Irwin & Barneby], morningglory, common ragweed (*Ambrosia artemisiifolia* L.), and other troublesome species (Askew et al. 2002; Ferrell and Vencill, 2003). Flumioxazin is also desirable because it provides weed control from soil residual activity, but a soil half-life of 13 to 18 d minimizes carryover concerns (Ferrell et al. 2003). However, lay-by applications of flumioxazin alone are not recommended because poor control of grass and sedge species is common (Anonymous 2006b). Therefore, flumioxazin is most often applied with glyphosate or MSMA to improve overall weed control.

An important consideration for PD applications is precision of herbicide placement. Many cotton producers apply glyphosate at lay-by for broad-spectrum weed control, with an apparent lack of visible injury in glyphosate-resistant cotton. However, glyphosate is readily absorbed by green cotton stems and accumulates in developing squares (Pline et al. 2001; Wills 1978). Accumulation of glyphosate in the fruiting

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Table 1. Cotton injury at 14 and 28 d after treatment (DAT) resulting from POST-directed herbicides applied at four stages of cotton growth. The herbicides were applied to either the bottom 2 cm of the cotton stem (low POST-directed [LPD]) or the lower 50% of the stem (high POST-directed [HPD]). The 95% confidence intervals are represented parenthetically beside the treatment means.

		Cotton height (cm)[a]					
Herbicide	Stem placement	20	30	40	50	Linear regression	
		% injury (14 DAT)					
Glyphosate + diuron	LPD	5 (± 4)	6 (± 4)	8 (± 5)	2 (± 2)	NS	—
Glyphosate + diuron	HPD	21 (± 8)	22 (± 6)	9 (± 4)	8 (± 5)	$y = -0.53x + 33.2$	$r^2 = 0.79$
Flumioxazin + MSMA	LPD	33 (± 5)	23 (± 6)	15 (± 5)	11 (± 6)	$y = -0.74x + 46.6$	$r^2 = 0.96$
Flumioxazin + MSMA	HPD	93 (± 5)	62 (± 9)	48 (± 9)	34 (± 6)	$y = -1.9x + 126$	$r^2 = 0.95$
		% injury (28 DAT)					
Glyphosate + diuron	LPD	4 (± 4)	6 (± 3)	6 (± 4)	1 (± 2)	NS	—
Glyphosate + diuron	HPD	16 (± 8)	21 (± 6)	10 (± 4)	3 (± 2)	$y = -0.51x + 30.1$	$r^2 = 0.69$
Flumioxazin + MSMA	LPD	31 (± 5)	30 (± 7)	11 (± 3)	10 (± 4)	$y = -0.82 + 49.2$	$r^2 = 0.83$
Flumioxazin + MSMA	HPD	94 (± 7)	66 (± 9)	32 (± 5)	28 (± 6)	$y = -2.3 + 136.2$	$r^2 = 0.92$

[a] Means differing by a margin greater than the sum of their respective confidence intervals are statistically different with a 0.95 level of significance; NS, not significant.

structures of cotton leads to floral abnormalities, pollen sterility, and boll abortion (Pline et al. 2002). Therefore, it is assumed that imprecise PD applications of glyphosate at lay-by could lead to reduced cotton yields due to boll repositioning and delayed maturity (Jones and Snipes 1999). Flumioxazin is also absorbed in green cotton stem tissue (Ferrell and Vencill 2003; Price et al. 2004) and has been shown to result in as much as 70% cotton injury with certain lay-by applications (Wilcut et al. 2000). However, no experiments have been conducted to document the impact of cotton height and herbicide placement on overall injury and yield with PD applications glyphosate and flumioxazin. Therefore, the objective of this research was to determine whether glyphosate + diuron or flumioxazin + MSMA applied PD at various cotton growth stages would result in reduced yield if that spray was directed to bark or green stem tissue.

Experiments were conducted in Citra, FL, in 2004, and in Dawson, GA, in 2005. Soil type at Citra was an Arredondo fine sand (Loamy, siliceous, hyperthermic, Grossarenic Paleudults) with 1% organic matter, and at Dawson, a Red Bay loamy sand (Fine-loamy, kaolinitic, thermic Rhodic Kandiudults) with $< 1\%$ organic matter. Glyphosate-resistant cotton[3] was planted on May 10, 2004, and June 8, 2005, at a rate of 9 seeds/m of row. Plots consisted of four 1-m rows that were 10 m in length. Conventional tillage systems were used at each site.

All plots received pendimethalin (0.92 kg ai/ha) at planting and glyphosate potassium-salt (1 kg ai/ha) at the four-leaf stage. Herbicides were broadcast from a tractor-mounted sprayer calibrated to deliver 187 L/ha. POST-directed applications consisted of glyphosate (1 kg ai/ha) + diuron (0.84 kg ai/ha) or flumioxazin (0.07 kg ai/ha) + MSMA (2.3 kg ai/ha). The PD applications were made when cotton reached 20, 30, 40, or 50 cm in height with a single nozzle CO_2-pressurized plot sprayer calibrated to deliver 187 L/ha. The spray was applied to both sides of the two center rows and was directed to the lower 2 cm of the cotton stem (low POST-directed [LPD]), or the lower 50% of the plant (high POST-directed [HPD]).

Cotton injury resulting from directed treatments was assessed visually using a 0 to 100 scale (0 representing no injury, 100 representing complete death). The degree of stunting, chlorosis, and necrosis caused by herbicide application was used collectively to determine the percentage of injury of treated plants. Percentage and cotton injury data were collected at 14 and 28 d after treatment (DAT). In September of each year, all plots received an application of ethephon[4] and thidiazuron[5] at 60% boll crack. After boll opening and defoliation was complete, the center two rows of each plot were harvested with a small-plot harvester.

The experimental design consisted of factorial treatments arrayed in a randomized complete-block design with four replications. The factorial arrangement contained four cotton-height stages (20 to 50 cm), two herbicides combinations, and two placements of the directed application. Also included were nontreated check plots for the two placements, yielding a total of 18 treatments. Data were analyzed with linear regression procedures. When no significant location by treatment interactions were detected, data were pooled and analyzed as a single data set. Arc sine transformations were conducted but did not yield results different from the analysis performed on the nontransformed data; therefore, nontransformed means are presented. Calculations for 95% confidence intervals were performed to separate treatment means.

Cotton yields in 2004 were reduced across all treatments because of the impact of Hurricane Jeanne that occurred on September 25. The storm caused cotton lint to be lost from bolls and some lodging occurred. However, each plot was affected similarly and harvest was accomplished approximately 3 wk later.

Results and Discussion

Herbicide Injury. Applications of glyphosate + diuron resulted in 2 to 22% injury, depending on cotton height and herbicide placement (Table 1). At 14 DAT, glyphosate + diuron directed to the lower 2 cm on the stem (LPD) resulted in $\leq 8\%$ injury for all cotton heights. Injury increased to 21 and 22% when the herbicide combination was applied HPD on the stem to 20-and 30-cm cotton, respectively. However, HPD applications produced $\leq 9\%$ injury after cotton reached at least 40 cm in height.

By 28 DAT, injury decreased between 21 and 1% for both LPD and HPD applications (Table 1). No statistical differences or trends were observed when glyphosate + diuron were applied LPD at 28 DAT. However, linear regression detected a significant inverse relationship between cotton height and herbicide injury for HPD applications of glyphosate + diuron. Using this model, it was extrapolated that applying glyphosate + diuron HPD after cotton reached 31 to 34 cm in height would result in 15% injury, a level generally viewed as acceptable by producers. Although these models did not represent the data with a high degree of accuracy (r^2 values between 0.69 and 0.79), the injury data confirm that cotton tolerance to glyphosate + diuron increases between the 30 and 40 cm height stage, particularly with HPD applications.

Flumioxazin + MSMA applications were more injurious than glyphosate + diuron (Table 1). When applied LPD, injury ranged from 33 to 11% for 20- to 50-cm cotton, respectively, at 14 DAT. Symptomology for 20- and 30-cm cotton was necrotic lesions on leaves, reddening stems, and stem girdling that eventually resulted in lodging. Necrosis of the lower leaves was the most common injury symptom for 40- and 50-cm cotton. By 28 DAT, little change in cotton injury was observed and still ranged from 31 to 10%. Additionally, no significant difference in slope or intercept was detected between 14 and 28 DAT data (data not shown). Regression procedures, performed on 14 DAT data, indicated a significant inverse linear trend and suggest that applications after cotton is 40 cm would result in $<$ 15% injury. These data are substantiated by the herbicide registration, which recommends that lay-by applications be delayed until cotton reaches 40 cm in height (Anonymous 2006b). Although MSMA can injure cotton, Askew and Wilcut (1999) reported no injury from MSMA applied PD. Therefore, cotton injury from flumioxazin + MSMA is attributed mostly to influence of flumioxazin.

Flumioxazin + MSMA applied HPD resulted in substantial injury at 14 DAT, which ranged from 93 to 34% when applied to 20- to 50-cm-tall cotton, respectively (Table 1). By 28 DAT, little recovery was observed. and injury between 94 and 31% was noted. Through extrapolation beyond our data set, regression analysis for 14 DAT data, suggests that delaying flumioxazin + MSMA applications until cotton reaches 58 cm in height would result in 15% injury. However, the herbicide injury symptoms from this application were necrotic lesions on all leaves contacted by the spray solution, whereas stems and upper leaves were unaffected. Therefore, it is unlikely that increasing cotton height would decrease injury to 15% because contact injury on treated leaves will occur regardless of physical height if applied HPD.

Previous reports have suggested that applying flumioxazin to small cotton or directing to green stems can cause "severe injury"; however, the degree and symptoms of injury were not indicated (Altom et al. 2000). In the current experiment, it was observed that HPD applications of flumioxazin directed to 20-cm-tall plants can result in cotton death and loss of stand.

Previous reports have determined that cotton safety to flumioxazin is related to increased herbicide metabolism with respect to plant age and restricted herbicide uptake in barked vs. chlorophyllous stems (Ferrell and Vencill 2003; Price et al. 2004). Price et al. (2004) found that flumioxazin metabolism increased ninefold as cotton matured from the 4 to 12-leaf stage. Additionally, Ferrell and Vencill (2003) found statistically greater absorption of flumioxazin when placed on chlorophyllous stems rather than barked stems. Therefore, as the plant matures, greater bark development and metabolic capacity lead to greater flumioxazin tolerance.

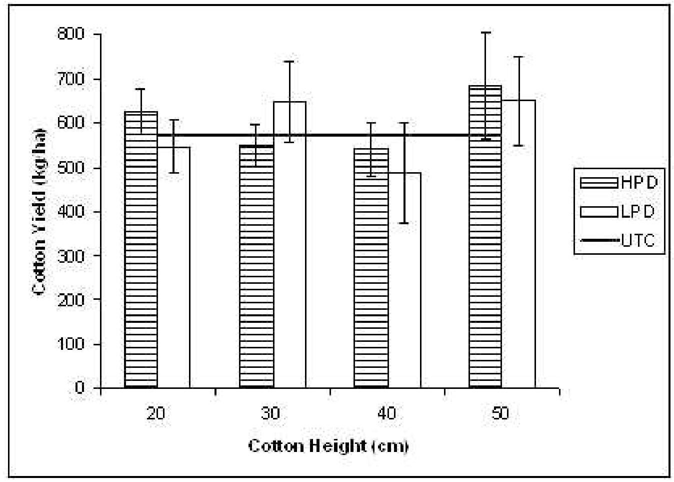

Figure 1. Cotton yield response from glyphosate + diuron applied POST-directed on 20- to 50-cm cotton, either low on the stem (LPD) or high on the stem (HPD). Abbreviations: HPD, high postemergence-directed; LPD, low postemergence-directed; UTC, untreated check.

Cotton Yield. The impact of herbicide injury on cotton yield was documented. No statistical interactions were detected for glyphosate + diuron applications; therefore, data were pooled across locations (Figure 1). All treatment combinations of cotton height at application and herbicide placement yielded equivalent to the nontreated check plots (580 kg/ha). Glyphosate + diuron applications resulted in as much as 22% injury at 14 DAT (Table 1), but no differences in cotton yield were observed, regardless of application timing or placement (Figure 1). Previous research has found that glyphosate applied after the four-leaf stage can result in boll abortion, delayed maturity, and yield loss (Jones and Snipes 1999; Pline et al. 2002). Although yield decrease was expected at the later application timing because glyphosate is readily absorbed by cotton stems (Pline et al. 2001), no yield reductions were detected with glyphosate + diuron applications.

A treatment by location interaction was detected for flumioxazin + MSMA applications, and data are presented independently (Figure 2). Cotton yield varied dramatically with application timing and placement of flumioxazin + MSMA. In 2004, LPD applications to 20-cm cotton resulted in significant amounts of injury, but the stand recovered, and no yield penalty was incurred. However, HPD applications in 20-cm cotton resulted in a 97% yield loss relative to the nontreated control. High levels of yield loss with this application was expected because $>$ 93% injury (Table 1) was observed, and that was largely manifested as loss of stand

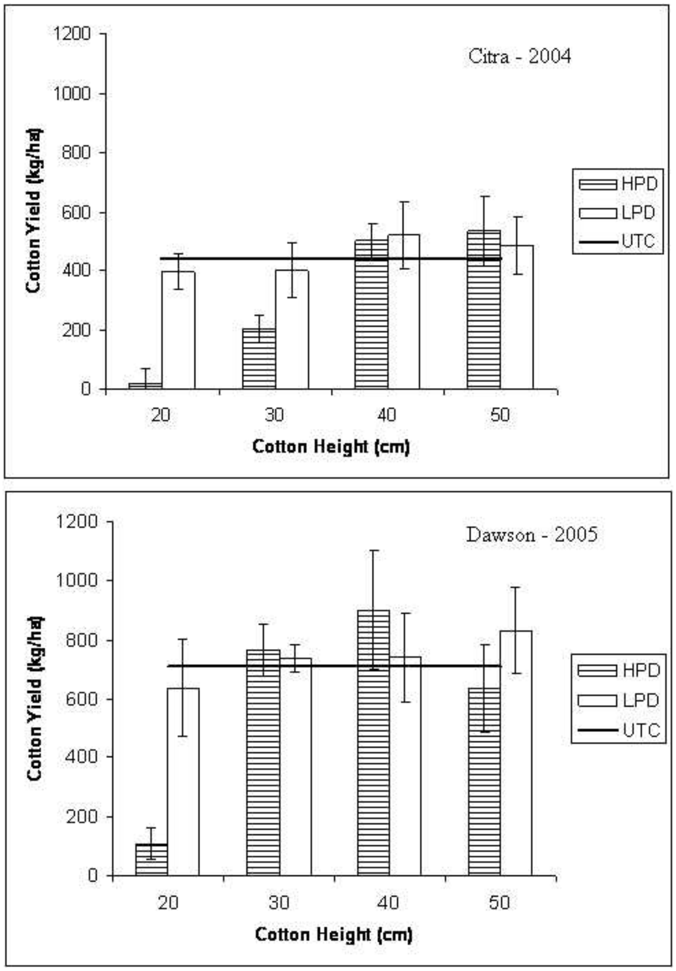

Figure 2. Cotton yield response from flumioxazin + MSMA applied POST-directed on 20- to 50-cm cotton, either low on the stem (LPD) or high on the stem (HPD). Abbreviations: HPD, high postemergence-directed; LPD, low postemergence-directed; UTC, untreated check.

population due to lodging and plant death. In 2005, overall yields were higher, but an 84% reduction in yield was noted for HPD applications to 20 cm cotton, whereas no yield impacts were observed for LPD applications (Figure 2). In 2004, a similar trend was observed for applications to 30-cm cotton. No yield effect was documented for LPD applications, but a 54% yield reduction was noted for HPD applications. However, in 2005, no yield reductions were observed for either application placement to 30-cm cotton. Although injury as high as 66% was noted with HPD applications to 30-cm cotton (Table 1), boll formation and retention was not impeded. For 40- and 50-cm cotton, no yield reductions from flumioxazin + MSMA applications were observed in either year or with either application placement (Figure 2).

A linear trend was observed with respect to relationship between cotton yield and cotton height at time of application. In 2004, linear regression of HPD data resulted in r^2 values of 0.93 ($y = 185.6x - 150.4$). From this model, HPD applications made before 41.8-cm cotton will result in cotton yields that are less than the nontreated. For LPD applications in 2004 and all data in 2005, no trends with respect to cotton height at application and yield were observed (data not shown).

From these data, it was concluded that glyphosate + diuron can be applied to cotton throughout the growing season with little concern of cotton injury resulting in yield loss. Although glyphosate registrations state that PD applications should avoid "contact of spray with the cotton leaves … to the maximum extent possible," no adverse effects were observed from improper glyphosate applications (Anonymous 2006a). Conversely, the flumioxazin registration states that applications should not be made before cotton is 40 cm tall (Anonymous 2006b). This recommendation was fully substantiated by the current research. Although LPD applications of flumioxazin did not result in cotton yield loss at any timing, unacceptable levels of injury were still observed on smaller cotton. Conversely, HPD applications have the potential to produce large yield losses. Therefore, precise application of flumioxazin is essential to maximize cotton safety and avoid yield loss. However, if the required level of application precision can not be attained, delaying the application until cotton reaches 40 cm in height will dramatically reduce the potential for yield reduction.

Sources of Materials

[1] Monsanto Company. 800 North Linbergh Blvd., St. Louis, MO 63167.

[2] Bayer CropScience LP. P.O. Box 12014, Research Triangle Park, NC 27709.

[3] DPL 555 BR cottonseed; Delta and Pineland Co., Scott, MS 38701.

[4] Prep. Bayer CropScience LP. P.O. Box 12014, Research Triangle Park, NC 27709.

[5] Dropp SC. Bayer CropScience LP. P.O. Box 12014, Research Triangle Park, NC 27709.

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